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Final Report for NAGW 224

Speckle Interferometry Applied to
Asteroids and Other Solar System Objects

August 1981 - July 1984

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RESULTS FROM NASA GRANT NAGW-224

A. Assumptions and Justifications

In an original and key piece of work, J. Cocke and J. Drummond developed the equations that express the major and minor axis dimensions and the orientation of the ellipse projected by a triaxial ellipsoid as a function of the three body axis dimensions and the direction of its spin axis. Thus if an asteroid can be modelled as a triaxial ellipsoid rotating about its shortest axis, and is smooth (no large craters, mountains, etc.), featureless (no albedo variations), and uniformly bright from limb to terminator, then as the asteroid rotates it projects a unique series of ellipses that change in size, shape, and orientation. Under the above assumptions the two dimensional image autocorrelation function has the same eccentricity and orientation as the projected ellipse, and the two dimensional image power spectrum has the same eccentricity as the projected ellipse, but rotated 90° . Therefore, it does not matter if the measurements of the dimensions and orientation of the ellipses are made in image, power spectrum, or autocorrelation space. The equations and derivations relating the projected ellipses back to triaxial ellipsoid body parameters are given in Section II of enclosure 1.

Based on our experience, all measurements are best performed in power spectrum space because noise appears as a bias (a background level) instead of the central spike of the autocorrelation function. Moreover, the seeing and modulation transfer function of the telescope can be calibrated away

from the power spectrum of the object by simply dividing by the power spectrum of a point source (star) after noise biases are subtracted. Details of the procedure can be found in enclosures 1-4; the latter, also describes the system used to obtain results thus far.

The assumption of a triaxial ellipsoid rotating about its shortest axis is a standard model (Burns and Tedesco, 1979), and is a natural outcome of asteroids in gravitational and/or hydrostatic equilibrium, such as would be formed by either coalescence or catastrophic collisions which result in "rubble piles" (Davis et al., 1979; Farinella et al., 1981; Catullo et al., 1984; Zappala et al., 1984). Rotation about the shortest axis is the most stable configuration, and even precession induced by perturbations would be expected to be damped out over a small fraction of the lifetime of the solar system.

For dark atmosphere-less bodies observed at low solar phase angles, uniform brightness is to be expected for all reasonable scattering laws (Dollfus and Zellner, 1979). Moreover, limb-darkening, which may be 5-10% for a completely smooth body, is reduced to less than 5% by roughness (French and Veverka, 1983), again supporting the treatment of an asteroid as a geometric scatterer.

Deformation of triaxial shape by the presence of mountains, craters, etc., might be important for small bodies, but should be negligible for larger asteroids. With a random distribution of deformations on a small body, it is still useful to treat the object as a triaxial ellipsoid with noise (irregularities of outline). And unless the deformation has a

different albedo, it has no effect on speckle observations unless it lies on a limb. Similarly, Fulchignoni and Barucci (1984) have shown that even for the largest craters known (in terms of the body diameter--for Phobos, Mimas and Thetis), the presence of a crater with the same albedo as the rest of the body cannot be detected in a lightcurve.

As for albedo variations, it appears that asteroids are uniformly coated a dull gray. The colors of asteroids are admixtures of various subtle shades of pink. Except for Vesta (Gradie et al., 1978; Dollfus and Zellner, 1979), most asteroids show no color, polarization, or spectrophotometric variation with rotation (Degewij et al., 1979). The current philosophy is adequately expressed by Burns and Tedesco (1979), who conclude that asteroid lightcurves are due primarily to shape rather than spottedness or irregularities. Accordingly, we proceed to interpret speckle observations with the assumptions stated at the beginning of this section.

B. Binary Asteroids

One of the original reasons for applying speckle interferometry to asteroids was to address the issue of asteroids with satellites. Perhaps the easiest class of objects to study with speckle are binaries, because both the autocorrelation function and power spectrum of a double system are simple to interpret. A binary star in autocorrelation space, for instance, appears as three "blobs," a center spot flanked by two mirror images of the companion; the power spectrum shows a characteristic interference fringe pattern.

We have performed analysis of speckle observations of four asteroids thus far (see below), including two of the three most favored binary candidates (Herculina, Pallas, and Victoria). 532 Herculina was suggested as a binary based on a secondary event during an occultation of a star on 7 June 1978 (Bowell et al. 1978; Van Flandern et al., 1979). From our observations we have placed an upper limit to the diameter of a satellite of the same albedo as Herculina at 50 km, having seen no indication of interference fringes at any rotational phase. From our own very early speckle observations in 1979, a large (but unresolved) satellite was suggested for Pallas. However, from new observations in 1982 that were better calibrated, we discount the earlier observation and place an upper limit for the size of a satellite at 55 km for the same albedo as Pallas. Among the data already obtained are many other possible binaries, but considering the results for Pallas and Herculina, we consider the search for satellites as incidental to determining the size, shape, and pole of each asteroid.

Another category of binary is the Pluto/Charon system. From our two observations (Enclosures 4 and 5) we predicted that the eclipse season should have begun by late 1984. This was borne out by observations made in January and February 1985 (Beatty, 1985). Once the eclipses start, further speckle observations will be unnecessary because the mutual masking of each disk twice each period will lead not only to intimate knowledge of each body, but a precise determination of the orbital parameters.

C. Reduced Asteroids

433 Eros

Eros is the cornerstone of our efforts to apply speckle interferometry to asteroids. It was chosen because it is perhaps the best studied asteroid of all as the result of a world-wide campaign in 1974/75, involving several techniques. Because, when we observed Eros in December 1981, and January 1982, the solar phase angles were 40° and 52° , we were forced to derive the equations necessary to express the size, shape, and orientation of the terminator as a function of the same parameters relevant to the ellipse projected by a triaxial ellipsoid. Without proper consideration of the effect of the terminator on the projected ellipse, we were not able to achieve sensible results. But taking the terminator into account we were able to find the size and shape of Eros that agrees well with the consensus model determined from 1974/75, and agrees even better with radar and detailed thermal modelling of radiometric observations (see enclosure 1).

However, the rotational pole we determined was 30° from the one found by other methods in the earlier opposition. But considering that most, if not all, of our assumptions may have been violated, the agreement is not all that bad. At the solar phase angles we observed Eros, scattering may have caused a non-uniform brightness from limb to terminator. Having been seen as redder and some 0.5 magnitudes brighter at oppositions before 1974, Eros may have strong hemispheric differences in albedo. And finally, the radar results of 1974/75 indicated that the rotational axis of Eros did not

equally divide the projected area, and therefore it is not a strict triaxial ellipsoid. Even a preliminary image reconstruction of Eros shows a distinctly non-ellipsoid shape. Nevertheless, all things considered, we were extremely encouraged with our results and proceeded on the same tack for other asteroids.

532 Herculina

Although no satellite was detected for Herculina, a giant bright complex was inferred from our observations as well as lightcurve data (enclosure 2). At certain points in the rotational cycle, the minor axis dimension became much too small (as measured in power spectrum space). Numerical experiments revealed that this phenomenon could be caused by a bright spot located on the limb of an ellipse. Locating the "spot", and estimating its relative reflectance, we were also able to account for its lightcurves, three of which showed one maximum and one minimum each rotation because the spot filled in one of the minima, and one which showed the classical two maxima and two minima per cycle because the spot was not visible deep in the asteroid's southern hemisphere.

511 Davida

Before our development of speckle interferometry, there were two methods of determining a rotational pole of an asteroid. Photometric astrometry takes advantage of the movement of the sub-Earth point across lines of longitude on the asteroid. By comparing epochs of extrema in a lightcurve it is possible to find the asteroid's rotational sidereal period, and by comparing the sidereal period to observed synodic periods, to

find the rotational pole. The other method, the amplitude-brightness-aspect relation, takes advantage of the movement of the sub-Earth point across lines of latitude on the asteroid. Observed from above its poles, an asteroid will appear at its maximum brightness and display a zero amplitude "lightcurve", and when observed in its equatorial plane the asteroid will display its maximum amplitude lightcurve and will be at its minimum brightness; this is the essence of the second technique.

Both methods of pole determination require numerous lightcurves from several oppositions over years. Our new technique yields the pole simultaneous with the three body axes dimension, and is derived from observations made over only one or two nights. In order to compare the three methods for finding a pole, an international campaign involving Davida was initiated. V. Zappala has used the amplitude-brightness-aspect relation for the lightcurves of Davida extending back to 1952 and R. Taylor will use photometric astrometry on the same data set. From only five speckle interferometry measurements of Davida on 3 May 1982, we have determined the asteroid's dimensions to be $(465 \pm 33) \times (358 \pm 39) \times (258 \pm 52)$ km and its rotational pole to lie within 26° of ecliptic coordinates $291^\circ, +37^\circ$ (see enclosure 3). Zappala's (private communication) preliminary results are axial ratios $a/b = 1.26$ and $b/c = 1.18$, with a pole at $303^\circ \pm 4^\circ, +34^\circ \pm 5^\circ$. Taylor's analysis is still in progress, but the agreement between the other two poles is satisfying. A collaboration among all the authors will result in a set of papers scheduled for Icarus that will intercompare the methods and examine the strengths and weaknesses of each.

2 Pallas

While the 1979 speckle observation of Pallas pointed to a highly elongated body, which was interpreted then as due to an unresolved companion of Pallas, some dozen speckle observations made in 1982, which were better calibrated because of many more observations of standard point sources, revealed that the asteroid is a single body, nearly spherical in shape, of dimensions $(534 \pm 29) \times (487 \pm 11) \times (486 \pm 11)$ km. Compare this to the shape as determined from an occultation and photometry: $(558 \pm 8) \times (526 \pm 12) \times (532 \pm 30)$ km, where the occultation observed an outline of $(559 \pm 6) \times (525 \pm 9)$. However a second occultation on 3 May 1983 revealed an outline of Pallas of $(530 \pm 2) \times (510 \pm 2)$, the minor axis being smaller than allowed by the model derived from the first occultation. Moreover, the pole used to derive that model has since been shown to be incorrect (Binzel 1984; Zappala et al. 1984). For a uniform asteroid the rotational axis c must be the smallest for stable rotation, but the triaxial ellipsoid model derived from the first occultation rotates about the intermediate axis and thus violates laws of physics unless the distribution of mass is non-uniform.

While the first occultation found Pallas to be smaller than previous determinations with polarimetry and radiometry, our latest results (and the second occultation) show Pallas to be even smaller still. Although our pole from the 1979 observation is only 7° from the one found by Zappala et al., our 1982 pole is some 70° from the latest photometric pole, and cannot explain any of the lightcurves. There is a strong systematic trend in the residuals of our second solution, and a detailed look at individual

power spectra and autocorrelations reveal that Pallas has albedo markings 5 to 10% brighter than the underlying surface, and are up to a quarter of the diameter of the asteroid. Furthermore, Harris (private communication) has Fourier analyzed the lightcurves and found that at least half of the power is in odd harmonics and can be attributed to spots.

In summary then, Pallas remains an intriguing object in spite of two occultations and speckle observations. As was done for Herculina it may be possible to derive a simple spot distribution from our observations that may reconcile lightcurves, speckle, and occultation results, and yield a mutually consistent pole.

D. Premature Conclusions

Although the bulk of our minor planet data remains unreduced, we indulge in some speculation after studying four asteroids, as a way of illustrating the science to be gleaned from a larger sample. We show the dimensions and poles for the first four asteroids of the project in Table I. The results for the first three asteroids may be considered secure and final. Further attention will be given to Pallas, but we will use both preliminary results nevertheless.

If there is a preferred direction of spin for asteroids, it might represent the original angular momentum vector direction for the single or few large parent bodies, or even the angular momentum vector of the solar nebula. More than likely, however, collisions have randomized the spins. If, however, collisions have had less of an impact than thought on the

TABLE I.

Summary of Asteroid Results from Speckle Interferometry at Steward Observatory

	a	b	c	RA	Rotational Pole (error)	Dec	Notes
433 Eros	40.5 ± 3.1 km 0"18	14.5 ± 2.3 km 0"06	14.1 ± 2.4 km 0"06	4°	($\pm 14^\circ$)	+43°	albedo .156 \pm .010
532 Herculina	263 ± 14 0"24	218 ± 12 0"20	215 ± 12 0"20	117°	($\pm 7^\circ$)	-39°	no satellite; bright spot 115 km wide, 75% more reflective
511 Davida	465 ± 33 0"24	358 ± 39 0"19	258 ± 52 0"13	287°	($\pm 26^\circ$)	+15°	possible "rubble pile", with density of 1.4 ± 0.4 gm/cm ³ $p_v = .034 \pm .001$
1979 2 Pallas	731 ± 38 0"40	547 ± 74 0"30	543 ± 18 0"30	228°	($\pm 4^\circ$)	-18°	no satellite; discrepant results attributed to extreme spottedness of face, further modelling continues.
1982	534 ± 29 0"48	487 ± 11 0"44	486 ± 11 0"44	294°	($\pm 8^\circ$)	- 6°	

evolution of the present asteroid population, then a primordial spin direction may still be evident. First note that the two largest asteroids Davida and Pallas, which are among the largest six known, have north poles within 22° (or 67° with the 1979 pole) of each other. This may be significant, but more data is obviously needed. Curiously, Herculina rotates in a retrograde sense with respect to the ecliptic plane, indicating no connection with any suspected primordial spin direction. Did a large impact uncover the bright area in its southern hemisphere and turn it "upside down"? Also note that none of the poles of the asteroids are particularly near the ecliptic north pole, as shown in Table II.

Perhaps there is a relation between directions of the orbital and the rotational angular momentum vectors. This quantity, called the obliquity (not to be confused with the same term explained in the appendix of enclosure 1), is also given in Table II. The average and standard deviation distance of the rotational pole from the orbital pole is $56^\circ \pm 20^\circ$ (or $52^\circ \pm 16^\circ$) which is consistent with the expected value for randomly oriented poles of $57^\circ \pm 22^\circ$.

If an asteroid is in hydrostatic as well as gravitational equilibrium, in other words is a liquid or more reasonably, is a gravitationally bound rubble pile (Davis et al. 1979), then it will have a particular shape, a sub-class of all triaxial ellipsoids called Maclaurian spheroids ($a = b > c$) and Jacobi ellipsoids ($a > b > c$). There is a unique relation between the

TABLE II.

Obliquities

Obliquity Between Rotational Pole and Ecliptic Pole

433 Eros		53°
532 Herculina		31° (149° with asteroid's <u>north</u> pole)
511 Davida		53°
2 Pallas	1982	74°
	1979	$57^\circ \pm \frac{90^\circ}{24^\circ}$
		$53^\circ \pm 18^\circ$

Obliquity Between Rotational Pole and Orbital Pole

433 Eros		64°
532 Herculina		28° (152° with asteroid's <u>north</u> pole)
511 Davida		54°
2 Pallas	1982	76° (104°)
	1979	$\frac{62^\circ (119^\circ)}{52^\circ \pm 16^\circ}$
		$56^\circ \pm 20^\circ$

Expected obliquity for randomly oriented poles $57^\circ \pm 22^\circ$

angular momentum and the ratios $a:b$ and $a:c$ for these figures. As Farinella et al. (1981) attempt to do, if we can find asteroids that have this equilibrium shape and assert that their gravitational forces dominate tensile strength, then from the size, shape, and rotational period we can determine the mean density of the asteroid, a particularly difficult parameter to obtain by any method. If a comparison to meteorites or earthly material can then be made, our knowledge of the bulk composition of asteroids will be greatly advanced, and asteroid modelling will have new constraints to address.

Because three of our four asteroids are very close to prolate spheroids ($a>b=c$), they cannot be considered as candidates for equilibrium figures, which are closer to oblate spheroids ($a=b>c$). The only exception is Davida. Within the error bars of our triaxial ellipsoid figure, Davida is an equilibrium figure: $465 \times 377 \times 244$. Its rotational period of 5.2 hours combined with its $a:b$ and $a:c$ yields a density of 1.4 ± 0.4 gm/cm³, if it is in hydrostatic equilibrium. This figure is low for meteoritic and earthly materials, but is plausible, for instance, if there is a large amount of void space. Eros is too small to even be considered as a candidate, presumably being a chip off another asteroid, and Herculina and Pallas are evidently dominated by tensile strength since their prolate shapes could not be supported by self-gravity alone. Since large amplitude short period asteroids, considered to be the best equilibrium candidates by Farinella et al., are also the best suited asteroids for study with speckle, we are further motivated to obtain more reductions. Table III

lists data for asteroids, already observed, which we hope to analyse with future funding. Not included in the table are 12 Victoria and 4 Vesta which are at intermediate stages of reduction. (See enclosure 6)

E. New Directions: Image Reconstruction

As part of the ongoing effort of the speckle interferometry group at Steward Observatory, support has been obtained from other sources (USAF, NSF) to develop image reconstruction techniques from speckle data. Preliminary attempts to produce images with various algorithms have been applied to the asteroids 433 Eros and 4 Vesta (enclosure 6). With successful image reconstruction we expect to verify the large (concave?) terminator on Eros observed at 40° solar phase angle, to detect the bright complex in the southern hemisphere of Herculina, to determine if an albedo gradient exists on Davida, and to show the spottedness of Pallas.

TABLE III.
Asteroid Data Bank

Asteroid	Dates Observed	# of pts	Solar Phase Angle	Apparent Size	Type	Binary
1 Ceres	10 Apr 82	2	13°	0.78	C	
9 Metis	5 Nov 82	13	17	.19	S	?
10 Hygiea	17-18 Jan 82	6	2	.26	C	
	9-10 Apr 82	4	18	.20		
16 Psyche	17-18 Jan 82	6	13	.14	M	
	10 Apr 82	6	13	.14		
21 Lutetia	26 Jan 83	4	2	.08	M	
88 Thisbe	4 Nov 82	10	5	.16	C	
115 Thyra	25 Jan 83	5	4	.10	S	
145 Adeona	26 Jan 83	10	11	.14	C	
182 Elsa	25-26 Jan 83	5	1	.3 ¹	S	?
349 Demboska	4 Nov 82	9	12	.11	R	

1. Observations were made primarily in the context of a binary system; instead of apparent sizes, expected separations are listed.

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